

# 論文の内容の要旨

## 論文題目

Development for an improved comparison of proton-to-antiproton charge-to-mass ratio

(陽子反陽子間の質量電荷比比較の精度向上に向けた開発)

## 氏名

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## 1 Introduction

CPT symmetry is known to be one of the most fundamental symmetries of the Standard Model of particle physics. It is defined as the symmetry of the laws of physics under the combined transformation of Charge conjugation (C), Parity transform (P) and Time reversal (T). A consequence of CPT symmetry is that the fundamental properties of matter-antimatter conjugates are identical, apart from signs. This has inspired experimental CPT tests in a variety of fields which compare these properties with high precision between matter and antimatter.

In this context, the Baryon Antibaryon Symmetry Experiment (BASE) collaboration [1] conducts stringent CPT tests by performing high-precision comparisons of the fundamental properties between the proton and the antiproton. The specific targets of BASE are their magnetic moments and the charge-to-mass ratios, which have now been compared and found to be consistent with CPT symmetry at relative precisions of  $6.9 \times 10^{-11}$  [2] and  $2.6 \times 10^{-9}$  [3, 4], respectively.

This thesis mainly discusses the experimental result obtained by BASE in 2014, and developmental works performed thereafter to improve the proton-to-antiproton charge-to-mass ratio comparison [5]. After these works, the frequency stability of in the apparatus has improved by a factor of  $> 3$  compared to the condition of the 2014 measurement.

## 2 Principles and methods

The principle of charge-to-mass ratio comparison is based on comparison of cyclotron frequencies of two particles in a Penning trap. The cyclotron frequencies of a proton and an antiproton in a common magnetic field  $B$  are expressed by

$$\nu_{c,p} = \frac{1}{2\pi} \frac{q_p}{m_p} B, \quad \nu_{c,\bar{p}} = \frac{1}{2\pi} \frac{q_{\bar{p}}}{m_{\bar{p}}} B. \quad (1)$$

with  $q_p, q_{\bar{p}}$  and  $m_p, m_{\bar{p}}$  representing charges and masses of the proton and the antiproton, respectively. The ratio between their charge-to-mass ratios is obtained by

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \left| \frac{(q/m)_{\bar{p}}}{(q/m)_p} \right| \frac{2\pi\mathcal{B}}{2\pi\mathcal{B}} = \left| \frac{(q/m)_{\bar{p}}}{(q/m)_p} \right|. \quad (2)$$

In practice, the negative hydrogen ion  $\text{H}^-$  is used as a proxy for the proton. This greatly reduces systematic corrections caused by inversion of the polarity of the trapping potential which is necessary in case of a direct proton-antiproton comparison [6]. We denote the antiproton- $\text{H}^-$  cyclotron frequency ratio as  $R_{\bar{p}\text{H}^-} \equiv \nu_{c,\bar{p}}/\nu_{c,\text{H}^-}$  which can be converted to that of antiproton-proton with sufficient precision for the measurement by a known value of  $\chi_{p\text{H}^-} \equiv \nu_p/\nu_{\text{H}^-}$  as (see Ref. [5] and references therein)

$$\left| \frac{(q/m)_{\bar{p}}}{(q/m)_p} \right| = \frac{R_{\bar{p}\text{H}^-}}{\chi_{p\text{H}^-}}. \quad (3)$$

The tool which is used to measure the cyclotron frequencies is a Penning trap, which provides confinement of a charged particle by a combination of a static magnetic field and a quadrupole electrostatic potential. In this field configuration, a particle has three eigenmodes of motion, called the modified cyclotron mode, the axial mode, and the magnetron mode respectively. Their frequencies are respectively denoted as  $\nu_+, \nu_z$  and  $\nu_-$ . The typical values for an antiproton in our system are  $\nu_+ \approx 29.656$  MHz,  $\nu_z \approx 640$  kHz and  $\nu_- \approx 7$  kHz.

Between these eigenfrequencies there is a relation called invariance theorem:  $\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$ , which is known to be robust against first-order trap imperfections [7]. Consequently, the cyclotron frequency of the particle can be determined by individual measurements of the three eigenfrequencies.

The BASE apparatus is equipped with non-destructive image current detection systems, each of them consisting of a high-quality superconducting resonator and a low-noise cryogenic amplifier. When a particle oscillates in a trap, it induces a minuscule image current in a trap electrode at its motional frequency. The axial frequency is measured by detecting this image current by an interaction with the detection system [8]. The two other eigenfrequencies are measured by a so-called sideband coupling method, in which one of these modes is coupled to the axial mode, and its frequency is determined from the modulation appearing in the axial frequency [9].

## 3 Charge-to-mass ratio comparison in 2014

The measurement scheme of the 2014 charge-to-mass ratio comparison is shown in Fig. 1. Antiprotons were provided by CERN's Antiproton Decelerator (AD).  $\text{H}^-$  ions were produced by a collision of the antiproton beam on a degrader structure at the entrance of the apparatus. After preparing a single antiproton and a single  $\text{H}^-$  ion, the measurement sequence of Fig. 1 (A) was executed. The cyclotron frequencies of the antiproton and the  $\text{H}^-$  ion

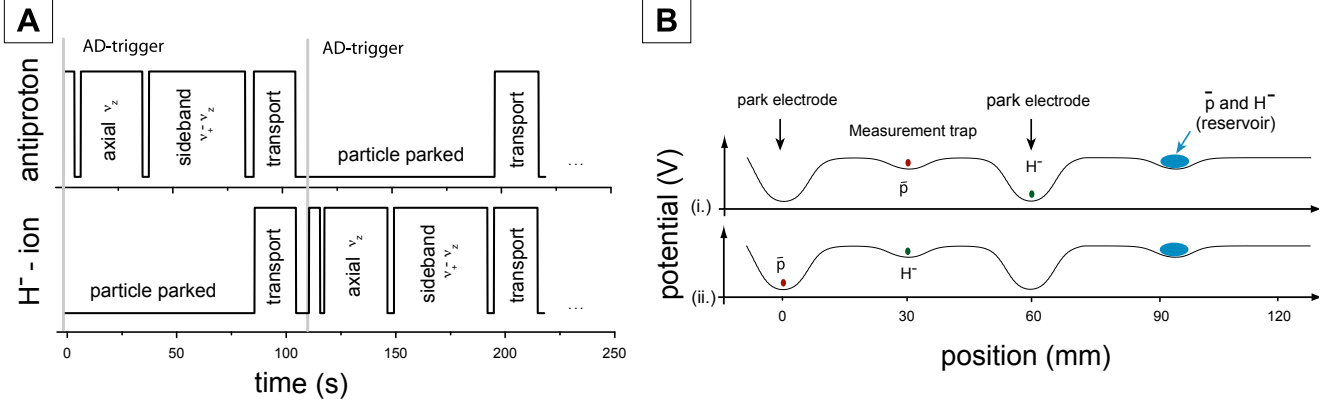


Figure 1: Measurement sequence (A) and potential configurations (B) of the 2014 charge-to-mass comparison. Adapted from Ref. [2].

were alternately measured by the above-described method. Fig. 1 (B) shows the potential configurations for the antiproton (Fig. 1 (B)(i.)) and the H<sup>-</sup> ion (Fig. 1 (B)(ii.)) applied during the measurements. While one of the two particles was being measured, the other was parked in one of the park electrodes adjacent to the trap. After each measurement, the particles were transported by sequential voltage ramps on the electrodes. Each of the exchange took only 15 s, which allowed 50 times faster data sampling compared to the previous work [6].

From 6521 sets of sampled cyclotron frequencies, the antiproton-H<sup>-</sup> cyclotron frequency ratio  $R_{\bar{p}H^-}$  was determined to be  $R_{\bar{p}H^-, \text{exp}} = 1.001\,089\,218\,755\,(64)(26)$ , after considering systematics corrections. This result translates to the proton-antiproton ratio of the charge-to-mass ratios of (Eq. (3))

$$\left| \frac{(q/m)_{\bar{p}}}{(q/m)_p} \right| - 1 = 1\,(64)(26) \times 10^{-12}. \quad (4)$$

This result is consistent with CPT symmetry, and is an improvement over the previous measurement by a factor of four in unit of absolute energy resolution [2, 6]. Both of the leading systemic correction and the major systematic uncertainty were caused by an adjustment of the trapping potential  $\Delta V \approx 5$  mV which was necessary to tune the axial frequency  $\nu_z \propto \sqrt{V/m}$  of each particle in resonance with the fixed frequency of the axial detection system. The voltage tuning caused a difference of the axial positions between the antiproton and the H<sup>-</sup> ion by about 30 nm. Together with a magnetic gradient  $B_1 = 7.58(42)$  mT/m, it caused a systematic uncertainty of 26 p.p.t. on the final result. Contributions of other systematic effects were on the order of  $10^{-13}$  or below.

## 4 Development for an improved measurement

To improve the 2014 measurement discussed in the last section, a two-fold strategy was conceived. The first was to eliminate the cause of the major systematic uncertainty of the last measurement. To eliminate the need of the tuning of the trapping voltage, we developed a new axial detection system a tunable resonance frequency. This will completely eliminate the primary source of the systematic uncertainty of the last measurement. The new tunable detection system installed in the experiment in 2017 was well functional, demonstrating a sufficient tuning range and highly reproducible properties against the tuning operation.

The second strategy was to improve the cyclotron frequency stability in the apparatus, which would allow sampling of high-quality data and will enable a reduction of the statistical uncertainty. For this purpose, an

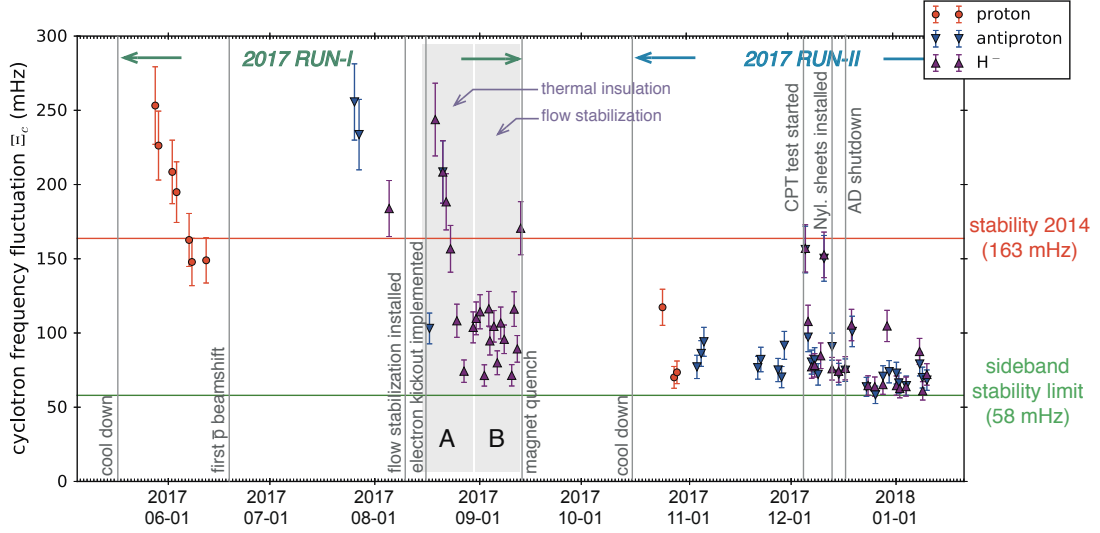


Figure 2: Development of the cyclotron frequency stability. The unit of the vertical axis is defined to be a measure of the cyclotron frequency fluctuations. The red horizontal line indicates the stability of 2014 condition. The fluctuation reached at the end of 2017 was about a factor of 3 smaller than in 2014, and close to the limit fluctuation attainable by the sideband coupling method employed for the measurement.

advanced magnetic field shielding system was developed. This is based on the principle of the self-shielding solenoid [10], which compensates the magnetic field variations by a shorted superconducting coil designed in a appropriate geometry. The system installed in 2017 was able to suppress external magnetic field fluctuations by a factor of 90, corresponding to an improvement of a factor of 9 compared to 2014 [5]. Another development made for this purpose was a monitoring system which continually recorded environmental conditions of the apparatus. Over the 2017 run, the conditions of the apparatus have been optimized by comparing the measured frequency stability against the information of the monitoring system. Development of the cyclotron frequency stability during the 2017 run is shown in Fig. 2 together with some of the optimization activities. The condition reached at the end was significantly better than the 2014 condition and would enable an improvement of the precision of the measurement by a factor of  $> 3$ .

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